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Sodium Laser Guide Star Adaptive Optics Imaging Polarimetry of Herbig Ae/Be Stars

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The future of high-resolution ground-based optical and infrared astronomy requires the successful implementation of laser guide star adaptive optics systems. We present the first science results from the Lick Observatory sodium beacon laser guide star system. By coupling this system to a near-infrared (J, H, K_s bands) dual-channel imaging polarimeter, we achieve very high sensitivity to light scattered in the circumstellar enviroment of Herbig Ae/Be stars on scales of 100-300 AU. Observations of LkHα 198 reveal a highly polarized, biconical nebula 10 arcseconds in diameter (6000 AU) . We also observe a polarized jet-like feature associated with the deeply embedded source LkHα 198-IR. The star LkHα 233 presents a narrow, unpolarized dark lane dividing

its characteristic butterfly-shaped polarized reflection nebulosity. This linear structure is oriented perpendicular to an optical jet and bipolar cavity and is consistent with the presence of an optically thick circumstellar disk blocking our direct view of the star. These data suggest that the evolutionary picture developed for the lower-mass T Tauri stars is also relevant to the Herbig Ae/Be stars and demonstrate the ability of laser guide star adaptive optics systems to obtain scientific results competitive with natural guide star adaptive optics or space-based telescopes.

Introduction

Diffraction-limited optical astronomy from the ground requires adaptive optics (AO) compensation to eliminate atmospheric wavefront disturbances. Bright stars may be used as wavefront references for this correction, but most astronomical targets lack nearby guide stars. High-resolution optical and infrared observations of these targets from the ground may only be accomplished using artificial laser guide stars (LGS) (*1*). Esentially all 8-10 m class telescopes are developing LGS AO systems, and future extremely large telescopes depend critically on LGS to achieve their scientific goals (*2,3*). Several LGS AO sytems have previously reported initial astronomical results (*4,5*). However, the only LGS AO system currently in use for regularly-scheduled scientific observations is that of the Lick Observatory 3-m Shane telescope (*6,7*). We present here the first scientific results from this system.

Herbig Ae/Be stars are very young stars with masses somewhat greater than that of the Sun, $1.5 \leq M/M_{\odot} \leq 10$ (*8*); they are the intermediate-mass counterparts of the more well-known T Tauri stars. Excess IR and mm emission shows that Herbig Ae/Be stars are associated with abundant circumstellar dust (*9*). This dust is likely the progenitor for debris disks such as those observed around more evolved A stars, such as β Pic (*10*).

On large spatial scales, the disk-like nature of the circumstellar matter around Herbig Ae/Be stars is well established. Flattened structures around several sources have been resolved on 100 AU scales (*11*), or have Keplerian kinematics (*12*). However, the evidence seems to be ambiguous on scales of tens of AU and below, with some authors arguing for a spherical geometry (*13*) and others favoring disks (*14*). Thus, although the IR excess of T Tauri stars almost certainly arises in a protoplanetary disk, the geometry of circumstellar material for Herbig Ae/Be stars is not as clear. By determining the geometry of the dust in Herbig Ae/Be systems, high spatial resolution observations can shed light on the existence of protoplanetary disks around this important class of massive young stars. Visible and near-infrared light (NIR) scattered from circumstellar dust around Herbig Ae/Be stars is typically polarized perpendicular to the scattering plane (*15*), making polarimetry a useful tool for probing the distribution of this material.

While Herbig Ae/Be stars are intrinsically very luminous, many are so distant or extincted that they are too faint to act as their own wavefront reference sources and thus require laser guide stars. Our program combines the angular resolution of laser guide star adaptive optics with the sensitivity to circumstellar dust of dual-channel imaging polarimetry.

Observations

Observations were made at the 3-m Shane telescope at Lick Observatory (Figure 1) using the AO system developed at Lawrence Livermore National Laboratory (*6*). The AO system feeds the Berkeley NIR camera known as IRCAL (*16*).

The Herbig Ae/Be stars LkHα 198 and LkHα 233 were observed on 2003 July 22 with standard J, H, and K_s broadband filters. The atmospheric seeing was 0.8 arcseconds at 550 nm, while the AO-corrected wavefront produced images with Strehl ratios $\sim 0.05 - 0.1$ at K_s band and full-width at half maximum (FWHM) resolution of 0.27 arcseconds. Table 1 summarizes our observations, and Figure 2 present three-color images with polarization vectors superimposed.

IRCAL's imaging polarimetry mode utilizes a cryogenic $LiYF_4$ Wollaston prism and rotating achromatic half-wave plate to produce two simultaneous images of orthogonal polarizations. The sum of the two channels gives total intensity, and the difference gives a Stokes polarization. The dominant noise source near bright stars in AO images is a "seeing halo" of uncorrected speckles. As these speckles are unpolarized and thus vanish in the difference image, dual-channel polarimetry achieves a contrast gain, enhancing the dynamic range in circumstellar environment (*17*). The observing techniques and data reduction methods are based on (*18*).

Circumstellar Dust Morphology, Color and Polarization

LkHα 198 The Herbig Ae/Be star LkHα 198 (V633 Cas) is located at the head of an elliptical loop of optical nebulosity extending 40 arcseconds to the southeast (*19*). This complex region includes at least three outflows, one seen in molecular emission (*20*) and two Herbig-Haro jets (*21*). There are also at least two additional Herbig Ae/Be stars in the immediate vicinity (V376 Cas and LkHα 198-IR) plus a millimeter source (LkHα 198-MM) believed to be a deeply embedded protostar (*22*). This proximity of sources requires high resolution observations to disentangle the various components and their relations (*23*). Figure 2 presents the discovery of a biconical nebula $\sim$10 arcseconds in diameter, oriented north-south, with polarization vectors concentric with respect to LkHα 198. The lobes of the reflection nebula are divided by a dark, unpolarized lane that we interpret as a strong density gradient towards the equatorial plane of a circumstellar disk and/or flattened envelope. The north-south orientation indicates that LkHα 198 is unlikely to be the driving force for the giant elliptical nebula or the molecular outflow to the southeast direction. However, it is consistent with LkHα 198 being the source for the Herbig-Haro flow at a position angle (PA, measured east from north) of 160 $^\circ$, a conclusion supported by the extension of LkHα 198's envelope along this position angle.

The embedded source LkHα 198-IR (*24*) is detected in our H and K_s band data 5.5 arcseconds from LkHα 198 at PA=$5°$. We detect a polarized, extremely blue, jet-like feature that extends $>$2 arcseconds from LkHα 198-IR at PA=105° (*25*). The polarization vectors of this apparent jet are perpendicular to its long axis, indicating that LkHα 198-IR is the illuminating source, and not LkHα 198. The jet appears to be half of a parabolic feature opening toward the southeast, with its apex at LkHα 198-IR and its southern side partially obscured by the envelope around LkHα 198. We suggest that northwest side of a bipolar structure around LkHα 198-IR may be hidden at NIR wavelengths by the large quantities of dust to the northwest indicated by mm observations (*26*). The orientations of circumstellar structures revealed by our images confirm that LkHα 198-IR is the best candidate for the origin of the Herbig-Haro outflow to PA 135°, though based on geometrical considerations we cannot entirely exclude the protostar LkHα 198-MM. By extension, the large elliptical nebula was most likely created by outflow from LkHα 198-IR, although we see it primarily in scattered light from the optically much brighter LkHα 198.

Several lines of evidence suggest that LkHα 198 is viewed at high inclination, $70° < i < 80°$. First, the equatorial plane is distinctive and clearly delineated as a feature in the J- and H-band polarized intensities. Secondly, the color of the biconical nebula surrounding LkHα 198 becomes increasingly red closer to the star, suggesting increasing foreground extinction or growing particle size as the line of sight approaches the equatorial region. Third, the morphology does not show significant lobe foreshortening nor is the more distant lobe extincted by dust in the midplane of the system. However, the system is not exactly edge-on: in J a point source is visible inside the dark lane in the polarized intensity image. This indicates that if a disk is present, the inclination is low enough that we are looking over rather than through the disk and can see the star. East-west nebulosity is also evident to either side of the northern component of the bipolar structure; we associate this with part of the fan-shaped nebula previously detected around LkHα 198, and not with the 40-arcsecond loop, which lies outside our field of view here. The polarization vectors are roughly centrosymmetric with respect to LkHα 198, indicating that LkHα 198 is the illuminating source.

LkHα 233 LkH 233 (V 375 Lac) is an embedded A5e-A7e Herbig Ae/Be star in the Lac OB1 molecular cloud at 880 parsecs which is associated with a blue, rectangular or butterfly-shaped reflection nebula 50 arcseconds in extent. Our imaging polarimetry reveals four distinct lobes bisected by a narrow, unpolarized lane with PA$\sim$150° (Fig. 2). The orientation of the lobes relative to the dark lane suggests that they are the limb-brightened edges of a conical cavity in a dusty envelope illuminated by a highly extincted star. This interpretation is consistent with reflection nebula models of a rotationally flattened infalling protostellar cloud with a polar cavity evacuated by an outflow (*27*).

We find that the intensity peak of the star is shifted SW relative to the polarization centroid, with the displacement increasing from 0.15 arcseconds at K_s to 0.35 arcseconds at J. This indicates that the lane consists of foreground material which is optically thick in the NIR and has a flattened spatial distribution consistent with a circumstellar disk or infalling protostellar cloud. We do not see the star directly, but instead view a scattering surface above the disk midplane, with the disk rotation axis pointing out of the sky plane to the southwest of the star.

Our high-resolution images clearly show that the dark lane has a warped, rather than linear, morphology. The apparent warping may be due to different projection effects with respect to the scattered light lobes, instead of a real twisting of flattened circumstellar material. The large radial extent of the dark lane suggests that for the most part it is associated with an equatorial torus characteristic of a flattened infalling protostellar cloud (*28*), and not a rotationally-supported disk. The nebulosity around LkHα 233 is extremely blue in the NIR, with its east-west extent decreasing from 6 arcseconds at J and H to 2 arcseconds at K_s.

Our results are consistent with low-resolution, wide-field optical imaging polarimetry (*29*), which suggests the presence of a large circumstellar torus in the northwest-SE direction and a bipolar reflection nebula to the NE and SW. Our interpretation is also consistent with the existence a blue-shifted, optical emission line jet (*30*) to the southwest (PA=250°). The jet both bisects the nebulosity and lies perpendicular to the proposed disk. The occultation of the redshifted [S II] lobe implies the presence of a < 600 AU radius disk; close to the star, two velocity components are resolved, indicating a low-velocity disc wind and a high-velocity Herbig-Haro jet. The geometry of the reflection nebula seen here indicates that this outflow is only poorly collimated ($\Delta\theta \sim 70^\circ$) despite the apparently narrow jet traced by optical forbidden line emission. Because [S II] line emission arises preferentially in regions denser than the critical density for this transition, the surface brightness distributions can take on the appearance of a highly collimated jet, despite the fact that the streamlines collimate logarithmically slowly (*31*).

Discussion

Observations of T Tauri stars have led to a general understanding of the origin of solar-type stars (*32*): The fragmentation and collapse of an interstellar cloud creates a self-gravitating protostar surrounded by a Keplerian accretion disk fed by an infalling, rotationally-flattened envelope. The disk mediates the outflows common to low-mass young stellar objects, which play a key role in the dispersal of the natal gas and dust. The extent to which this paradigm applies to the more massive Herbig Ae/Be stars is unclear. The Herbig Ae/Be stars are rarer than T Tauri stars because of the steep slope of the initial mass function and the comparative brevity of their pre-main-sequence evolution. Herbig Ae/Be stars are thus on average more distant than T Tauri stars, and high-resolution observations such as those presented here are crucial to their study.

LkHα 198 and LkHα 233 are both classified as Group II Herbig Ae/Be stars, meaning they have infrared spectra that are flat or rising towards longer wavelengths. This has been interpreted to mean that they are young stars that may or may not possess circumstellar disks but do possess circumstellar envelopes which are not confined to a disk plane. We observe such envelopes around both of our sources in the form of centrosymmetrically polarized biconical nebulosities.

LkHα 233's limb-brightened appearance provides unambiguous evidence for the presence of cavities swept out by bipolar outflow from the star, but the situation is not so clear for LkHα 198. The absence of limb brightening may be evidence that LkHα 198 lacks polar cavities. The observed morphology can be explained by the illumination of a cavity-free, rotationally-flattened envelope by the central star. The conical pattern does not indicate collimation of starlight by a protoplanetary disk, as the opening angle is too narrow: shadowing by dusty protoplanetary disks is set by the dust sublimation temperature, which for typical Herbig Ae/Be parameters produces an opening angle of 160°–170° (*33*).

One notable difference from the cavity-free infalling envelope models is that the opening angle of the nebulosity in those models increases with wavelength, while the observed opening angle is constant. There is a low-contrast dark, linear structure, which runs along the cone axis of the envelope around LkHα 198 , that may be associated with a cavity in the process of formation. Nonetheless, if we are correct in associating the southern Herbig-Haro jet with LkHα 198, the lack of limb brightening from a well-developed cavity is contradictory. This difficulty could be resolved if the outflow is precessing and intermittent.

For both LkHα 233 and LkHα 198, the peak polarization differs between the two lobes. These asymmetries may indicate the sign of the inclination for each object. For LkHα 198, the polarization in the southern lobe of the bipolar nebulosity is generally 10-15% higher than the northern lobe at all wavelengths (35% vs. 20% at H, for instance), suggesting that the southern lobe is oriented towards us. For LkHα 233, the southwest lobe is 14% polarized on average vs 26% for the northeast lobe, again indicating that the southern lobe is facing us. This result is consistent with the fact that the blueshifted end of the CO jet is in the southwest, and with the fact that the intensity peak of LkHα 233 is shifted to the southwest relative to the polarization centroid.

In general, LkHα 233 appears to be a more evolved system, with a well-defined cavity swept out by bipolar outflow and bisected by a very dark lane. LkHα 198 seems to be a less evolved system, which is only in the early stages of developing bipolar cavities and possesses lower extinction in the apparent disk midplane.

While our sample of Herbig Ae/Be stars is limited, we observe circumstellar enviroments consistent with the infalling envelope models developed for T Tauri stars. These data suggest that the process of envelope collapse has similar phases, despite the large disparities in mass and luminosity between these two classes of young stars. The fact that there is evidence for a rotationally-flattened infall envelope suggests a common origin for Herbig Ae/Be stars and T Tauri stars. This morphological similarity leads us to infer that the conservation and transport of angular momentum is the dominant physical process for both classes of stars. Formation pathways for intermediate mass stars that invoke new physical mechanisms, such as magneto-hydrodynamic turbulence (*34*) or stellar mergers (*35*), do not appear to be necessary.

Laser guide star adaptive optics enhances the capabilities of ground-based telescopes to study a wide variety of astrophysical phenomena, not just those near bright natural guide stars. As LGS AO systems mature further, techniques such as those presented here will further illuminate the nature of circumstellar environments around faint young stars.

References and Notes

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Figure 1: The Lick Observatory LGS AO system in operation on 2003 July 22. Faint cirrus clouds are illuminated by the Moon, while the yellowish cast of the dome is due to the street lights of nearby San Jose. The atmospheric wavefront reference source was produced by a laser tuned to the sodium D2 line, which excites mesospheric sodium (*7*). The 589 nm light is generated by a tunable dye laser pumped by a set of frequency-doubled solid-state (Nd:YAG) lasers. The laser typically projects 11-14 W of average power into the sky with a pulse width of 150 ns and a pulse repetition rate of 13 kHz. The science targets were used as tip-tilt references.

Table 1: Target Summary

Object	V (magnitudes)	Distance (parsec)	Spectral Type	Luminosity ($L_\odot$)	Mass ($M_\odot$)	Time per band (s)
LkHα 198	14.3	600	A5e-A7e	5.6	1.2	960
LkHα 233	13.6	880	A5e	28.2	2.6	1440

V magnitude, distance, luminosity, and mass are from (*9*). Each target was observed for the same amount of time in J, H, and K_s, divided equally between Stokes Q and U observations. Typical exposures were 30-90 s in duration, with small dithers performed every few exposures.

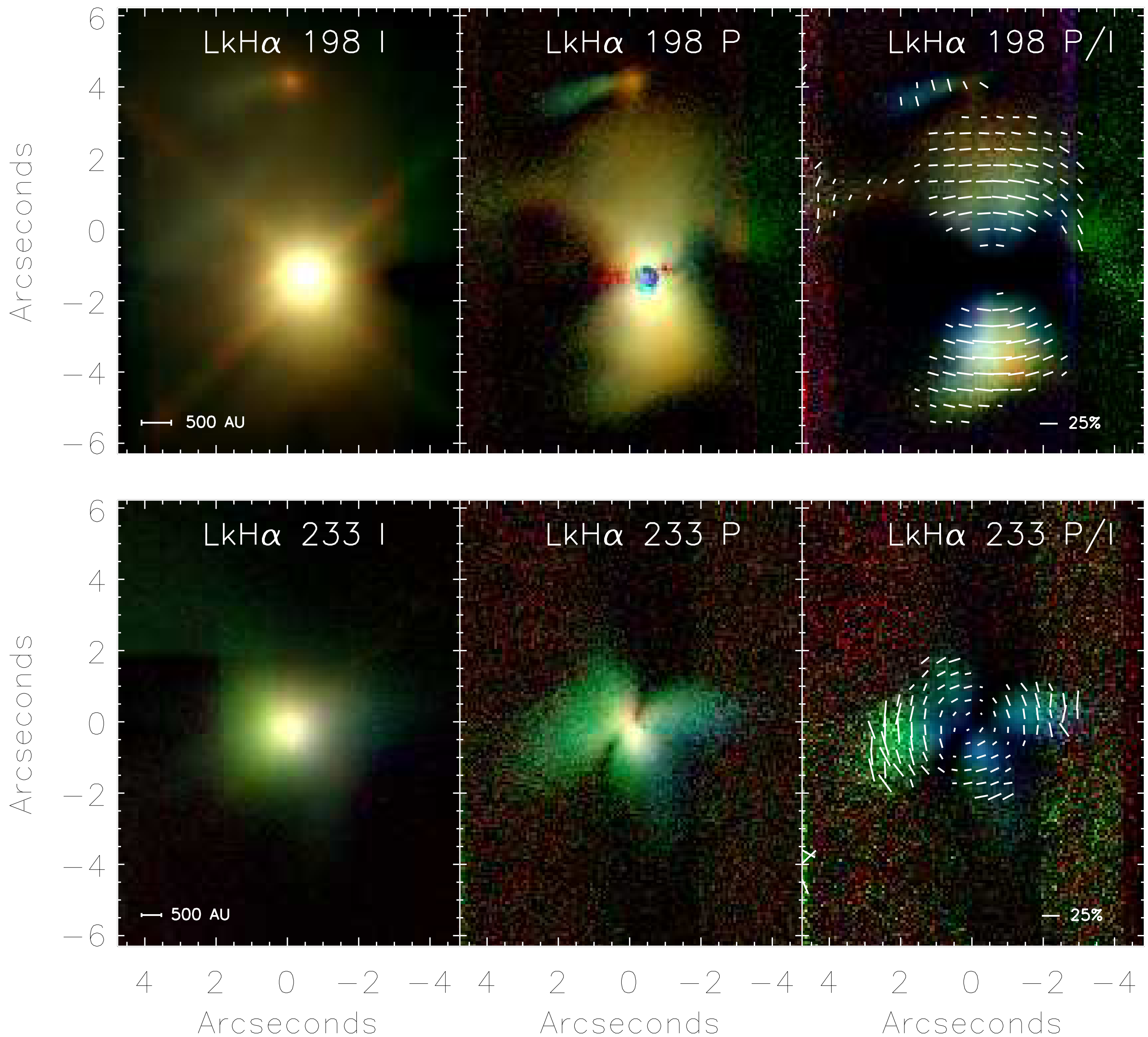

Figure 2: Three-color JHK_s mosaics of LkHα 198 and LkHα 233. Plotted from left to right for each object are the total intensity (Stokes I), the polarized intensity (Stokes "P" $= \sqrt{Q^2 + U^2}$) and the polarization fraction (P/I). I and P are displayed using log stretches, while P/I is shown on a linear stretch. Red is K_s band, green H, and blue J. Polarization vectors for H band are overplotted on the P/I image; while the degree of polarization changes somewhat between bands, the position angles do not vary much. The dimmest circumstellar features detected in our polarimetric observations are approximately $1 - 2 \times 10^4$ fainter than the stellar intensity peaks. IRCAL is sensitive to polarization fractions as low as a few percent, resulting in a signal-to-noise ratio of 5-10 per pixel for the typical polarizations of 15-40% observed around our targets.

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